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CONSIDERATIONS TO ACHIEVE DIRECTIONALITY FOR GAMMA RAY LASERS

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CONSIDERATIONS TO ACHIEVE DIRECTIONALITY FOR GAMMA RAY LASERS

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Abstract

This study concerns a method of alignment of nuclei for a gamma ray laser and a means of achieving preferential emission of radiation along the crystal axis. These considerations are important because it probably is not possible to achieve reflection of gamma radiation in order to have photons make multiple passes through an active region. Atomic alignment has been achieved by materials researchers who have made composite structures composed of needle-like single crystals all with the same orientation and all pointing in the same direction contained in a matrix of cobalt or nickel. The proposed method of preferential emission of radiation along the aligned needles is to have a symmetric field gradient at the nucleus and a sequence of excited levels of spin and parity 2^+ and 0^+. The proposed scheme will reduce the density of excited states required for lasing and reduce the linewidth due to inhomogeneous broadening. Mossbauer absorption experiments intended to test these ideas are outlined.

I. Introduction

Historical Review

Recent review articles have indicated the substantial difficulties that exist in achieving a gamma ray laser.[1,2] The state of knowledge of the interactions of the nucleus and its surroundings was insufficient to allow those who conceived the concept of the gamma ray laser to foresee many of the problems.[3,4]

Perhaps the most difficult of the originally perceived problems, how to obtain a density of inverted states sufficient to have lasing, is still with us. There is, however, no known fundamental limitation to achieving high densities and man's continuing effort to make his power sources (fission reactors, fusion reactors and particle accelerators) more powerful may someday solve the intensity problem.[5]

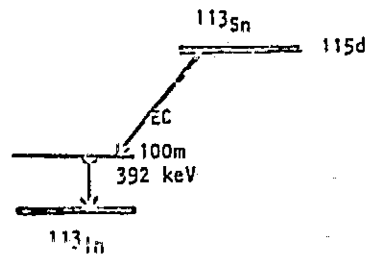
An originally unappreciated problem, that fluctuating nuclear interactions with the surroundings that broaden nuclear levels to the extent that resonant absorption and stimulated emission are unlikely, is the subject of this paper. The static interaction of the nuclear quadrupole moment with an internal electric field gradient is considered as a means to achieve:

1) energy level splitting
2) desirable directivity of the emitted gamma radiation
3) a practical physical material with geometry suitable for a laser.

The conclusion of this paper unfortunately will not give a solution to all of these problems but is rather a suggestion as to what nuclear energy level configuration is desirable for a gamma ray laser. These considerations will serve to guide our future experimental research studies.

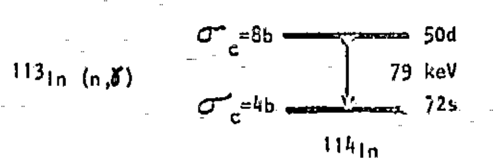
General Considerations for Population Inversion

To achieve population inversion of nuclear levels is not difficult if one takes advantage of beta decay and nuclear isomerism. This is illustrated with the decay of ^{113}Sn.



A freshly separated source of ^{113}Sn will decay into the isomeric level of ^{113}In and population inversion will exist for several hours; eventually the ground state population increases and exceeds that of the isomeric level.

Population inversion can be achieved by nuclear reactions as shown by the example:



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Energy Requirements

The energy of the isomeric level is a consideration since the parasitic absorption by atomic electrons is decreased for more energetic photons whereas the cross section for stimulated emission is proportional to λ^2 and therefore favors low energy transitions. Another consideration favoring low energies is that photon energies must not be decreased by the recoil of the emitting nucleus. The so-called recoilless fraction decreases exponentially with increasing energy, becoming negligible above 150 keV. In this note we are proposing the use of only certain kinds of nuclear levels because one can thereby achieve: 1) unidirectional transmission of gamma rays, 2) by removing level degeneracy, photons with less spread in energy than otherwise and 3) an energy matching of the photon with the levels that are to undergo stimulated emission.

II. Proposal

Electric Quadrupole Transitions

Gamma radiation emitted between nuclear levels of spin and parity 2^+ and 0^+ or 0^+ and 2^+ actually involves transitions to or from sublevels of the 2^+ state since that level splits into $m = \pm 2$, ± 1 and 0. If there is an electric field gradient q which is axially symmetric with respect to the crystal axis then the sublevels split as shown in figure 1, and the three transitions $\Delta m = \pm 2$, $\Delta m = \pm 1$, and $\Delta m = 0$ are shifted in energy as shown.

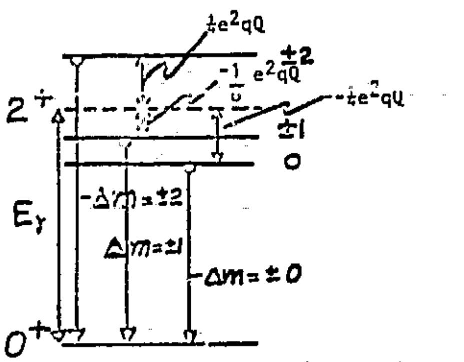


Fig. 1 Energy level splitting of 2^+ level in a field gradient and also showing the three transitions to a 0^+ level.

The angular distribution of the gamma radiation with respect to the symmetry axis is given by

$$W(\theta) = \frac{1}{2}(1 - \cos^4\theta) \text{ for } \Delta m = \pm 2$$

$$W(\theta) = \frac{1}{2}(1 - 3\cos^2\theta + 4\cos^4\theta) \text{ for } \Delta m = \pm 1$$

$$W(\theta) = 3(\cos^2\theta + 4\cos^4\theta) \text{ for } \Delta m = 0$$

These radiation patterns are shown in figure 2.

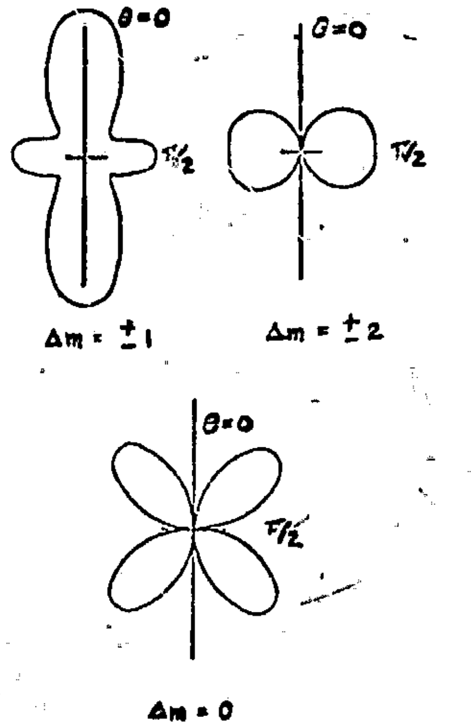


Fig.2 Electric quadrupole angular distributions for the three components of a 2^+ level.

Combining the information of the two figures shows that the $\Delta m = \pm 1$ component is emitted along the crystal axis with an energy $E_\gamma - 1/8 e^2 qQ$. If the energy of the gamma ray is not too high and the Debye temperature of the solid is appropriate then there may exist a large fraction of recoilless photons. When one of these photons interacts with another nucleus in the isomeric state then stimulated emission will occur. However, only the $\Delta m = \pm 1$ transition will have an energy match with the incident photon. The gamma rays arising from the other two transitions would emerge perpendicular to the symmetry axis.

These ideas have been tested by carrying out Mossbauer absorption experiments for the $2^+ \rightarrow 0^+$ transition. The absorption of the recoilless photon in a WS_2 single crystal (hexagonal close packed) which has an electric field gradient along the c axis at each tungsten nucleus gave the results shown in figure 3a.[6] Only a single component, $\Delta m = \pm 1$, is resonantly absorbed when the incident photon is oriented along

c axis. A similar result is shown in figure 3b for the photon of the $2^+ \rightarrow 0^+$ transition in ^{178}Hf, which was absorbed in single crystal of hafnium metal.

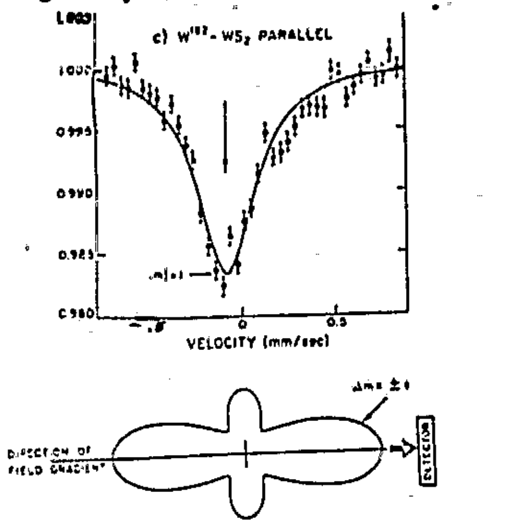


Fig.3a Mossbauer transmission experiment of the $2^+ \rightarrow 0^+$ transition in WS_2 for the case when the incident photon is aligned with c axis of the crystal.

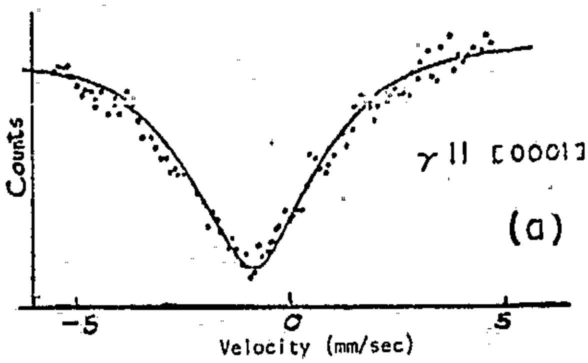


Fig.3b Same as 3a except the $2^+ \rightarrow 0^+$ transition is transmitted in Hf metal single crystal.

In both cases the results confirmed that the $\Delta m = \pm 1$ transition is absorbed parallel to the symmetry axis.

Filamentary Alignment of the Nuclear Isomers

It was recognized by the inventors of the gamma ray laser concept that the alignment of the active atoms on a single axis could solve the problem of the non-existance of mirrors with which to form a cavity. Whisker crystals were suggested as a possible materials configuration.[7]

The idea of the whisker configuration can be combined with the anisotropic distribution of the $\Delta m = \pm 1$ quadrupole transition. What is required to do this is an electric field gradient along the whisker filament and the crystal structure of the filament to be symmetric about the whisker axis. The concept is shown in figure 4.

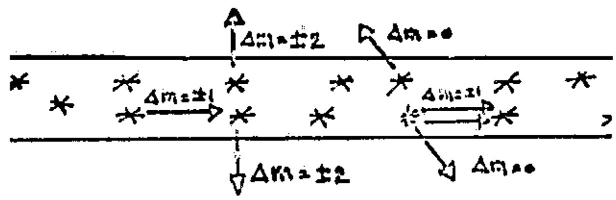


Fig.4 Schematic illustration of nuclei in isomeric states *, aligned in filaments and emitting quadrupole radiation when an electric field gradient is present and is in the filamentary direction.

Most of the photons from $\Delta m = \pm 2$ and $\Delta m = 0$ transitions will be emitted out of the whisker; those few emitted along the whisker axis will be shifted in energy from the $\Delta m = \pm 1$ photons. The axially directed, $\Delta m = \pm 1$ photons will have less energy spread than would photons from a degenerate 2^+ level.

Directionally Solidified Eutectics (DSE)

Materials scientists are working on the development of reinforced materials where the strengthening members are filaments or lamellae of a precipitated eutectic. The precipitates are single crystal and aligned and are often spaced in a rather regular array in the matrix alloy. Such a material is shown in figure 5, a SEM view of a directionally solidified rod of nominal composition Co-15 Cr-20 Ni-10.5 Hf -.7C; prepared by V.G. Kim of NASA's Lewis Research Center.[8] In this case the precipitate is HfC and the matrix material has been etched away to show the protruding HfC filaments.

Fig.5 Structure of directionally solidified TaC-15Cr-20Ni-Co alloy.

The DSE alloys offer an obvious solution to the gamma ray laser requirement for aligned nuclei. The requirement of symmetry and an electric field gradient along the filament can be achieved in either two ways:

1) the precipitate can have a crystal structure which has isotropy about a crystal axis and the crystal axis is parallel to the filament axis, an example of such a structure is tungsten disulfide, a hexagonal close packed crystal, or

2) the precipitate can have an isotropic structure, e.g., cubic, and be strained in the filamentary direction by differential expansion coefficients between the precipitate and the matrix. The strain of the crystal would be expected to destroy the symmetry in the strain direction and give rise to an electric field gradient.

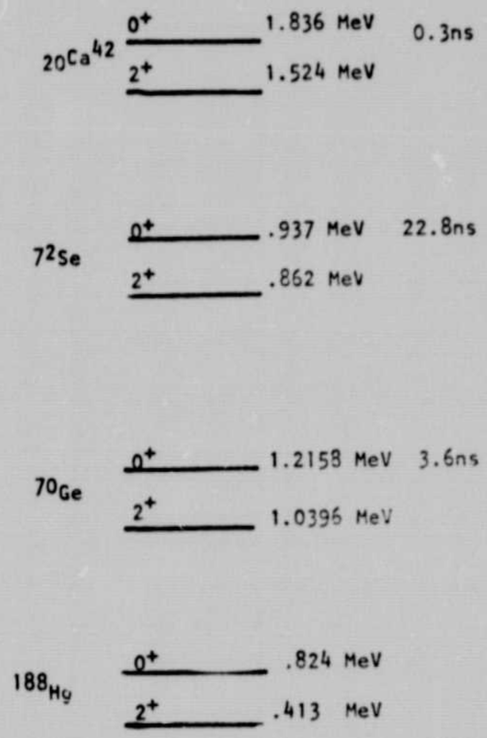
Mossbauer absorber measurements will be made using the HfC reinforced composite as the absorber of the 93keV gamma from the $2^+ \rightarrow 0^+$ transition in ^{178}Hf. If the HfC has become noncubic, this should be detectable in the shape of the absorption line.

Preferred Level Arrangement

As we have indicated, a long-lived isomer having a spin sequence of levels $2^+ \rightarrow 0^+$ or $0^+ \rightarrow 2^+$ in a host having an axially symmetric field gradient will provide directed gamma radiation.

Additional considerations favor the $0^+ \rightarrow 2^+$ sequence, i.e., the isomeric state should be the 0^+ and the lower state 2^+ and both states should be above the ground state. With this arrangement, there will be no nuclear absorption of the recoilless gamma rays and there will be no broadening of the 0^+ level due to the stochastic field gradient or magnetic fields at the nucleus since a 0^+ state has no moment. The only factor then broadening the 0^+ level will be the inhomogenous isomer shift. We prefer the 2^+ level to be short-lived, then its natural width will be far larger than the isomer shift, thus an energy match between the recoilless gamma ray and the energy difference between $0^+ \rightarrow 2^+$ is assured and stimulated emission can occur.

The question as to whether the preferred nuclear level arrangement exists can only be answered by research studies in isomerism. A number of known $0^+ \rightarrow 2^+$ isomers are given below.



Isomeric states with longer lifetimes should be sought for the gamms ray laser. In addition to the traditional islands of isomerism, many quasiparticle states, bandheads of decoupled bands and nuclear levels with large changes in nuclear shape may provide the longer-lived isomeric state of the $0^+ \rightarrow 2^+$ type.

Conclusion

The rationale for searching for a nuclear isomer with a 0^+ spin and parity and decaying by means of a $0^+ \rightarrow 2^+$ transition has been given. At this point no suitable isomer is known. The directionality of emission which a laser requires can be achieved in filamentary structures with symmetry about the filamentary axis. Materials research in directionally solidified, precipitate reinforced, alloys should be watched for developments which may have the symmetry and electric field gradient required to achieve directional gamma ray emission.

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